# ADJUSTMENTS IN RIVER CHANNEL GEOMETRY ASSOCIATED WITH HYDRAULIC DISCONTINUITIES ACROSS THE FLUVIAL–TIDAL TRANSITION OF A REGULATED RIVER

ANGELA M. GURNELL

*School of Geography, University of Birmingham, Birmingham B15 2TT, UK*

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## ABSTRACT

Major hydraulic discontinuities along lowland rivers may be caused by water impoundment behind weirs, by tributary floods, and by tides. An analysis of the geometry of 122 surveyed channel cross-sections located on an 18 km reach of the lower River Dee identifies up to three levels in the bank profile representing minima in the width:mean depth ratio, and distinct changes in the geometric properties of the channel to these three levels in a downstream direction and within four stretches influenced to varying degrees by hydraulic discontinuities created by a weir and by tidal overtopping of the weir. Simple modelling combined with field observations suggest possible processes that may control the observed changes in channel morphology. © 1997 by John Wiley & Sons, Ltd.

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## INTRODUCTION

The dominant controls on river channel size and form are the discharge and sediment transport regimes and the character and composition of the channel boundary. Discharge and sediment transport regimes represent the delivery of water and sediment from the upstream catchment area under the influence of climate, topography, rock type and vegetation cover (Knighton, 1984). The supply and delivery of water and sediment are affected by a variety of anthropogenic influences within the catchment and river channel system, including land use, flow regulation, water abstraction and wastewater disposal, and channel modifications, all of which can impact upon river channel size and form (e.g. Downs, 1994). The complex nature of the interactions between river channel process and form has been addressed in many reviews (e.g. Ferguson, 1986; Knighton, 1987; Miller, 1991; Rhoads, 1991, 1992; Park, 1995; Pizzuto, 1992). Huang and Warner (1995), combining results of laboratory flume studies with information from alluvial channels, have recently suggested that the downstream hydraulic geometry of river channels is primarily determined by four factors: discharge, channel slope, channel average roughness and the sediment composition of the channel boundary. Knighton's (1987) review provides one of the few attempts to consider explicitly the impact of downstream discontinuities in the factors controlling river channel geometry. He notes the important impact of structural controls on slope: the discontinuous input of sediment as a result, for example, of mass movements from the channel banks and adjacent hillslopes; sudden changes in bed composition at gravel-bed to sand-bed transitions; and abrupt changes in discharge and sediment transport at tributary junctions. However, none of the above focuses upon the influence of discontinuities associated with steady or unsteady disturbances to river flows which impact on the energy gradient, such as the influence of tides, non-synchronous mainstream and tributary flows, and hydraulic structures such as weirs. Such disturbances, their interaction with the transmission of water and sediment during floods, and their impact on bank sedimentation, form the focus of this paper, which considers channel cross-sectional morphological change along a river reach where the other three factors identified by Huang and Warner (1995) either exhibit little variation (discharge, sediment composition of the channel boundary, particularly the banks), or do not vary systematically along the reach (roughness).

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Major disturbances to the energy gradient along a river influence the flow velocity and thus the shear stress imposed on the channel boundary. They also influence flow cross-sectional area and thus the spatial extent of channel and floodplain directly affected by fluvial processes during discharge events of a particular magnitude. Therefore, such disturbances would be expected to have a major influence on the location and magnitude of sediment mobilization and deposition, and thus on river channel size and geometry (e.g. Magilligan, 1988). Disturbances of the energy gradient occur in relation to hydraulic control structures such as weirs, in association with fluctuating water levels in tributary rivers whose flow regime is out-of-phase with that of the main river, and in rivers which are subject to tidal influences. Such disturbances can affect very substantial lengths of river where the floodplain and channel slopes are low, as is the case in the lower reaches of major river systems. Evidence of the impact of such hydraulic disturbances on river channel geometry can be obtained from: Meade *et al*. (1991), who consider the impact of backwaters created in the main stem of the Amazon by flood inputs and floodplain storage of water from major downstream tributaries; Rasid and Phillips (1989) who describe the impact of Lake Superior water levels on morphological adjustment within a floodway; and Inokuchi (1989), who investigates the channel morphology of the Lower Mississippi including possible modification by tidal influences. In the case of tidal influences, the research focus has been mainly on estuaries, on salt-water flows within river channels, and on the rate and character of sedimentation over different timescales (e.g. Cooper, 1993; Lanier *et al*., 1993; Mamas *et al*., 1995; Sanford *et al*., 1991), rather than on river channels, the backing-up of freshwater upstream of the tidal waters, and the morphological effects of the modified energy and sediment transport regimes, which are the theme of this paper. However, Renwick and Ashley (1984) considered the complete transition from fluvial to estuarine conditions on the Raritan River, New Jersey, where they identified a distinctive sequence of downstream changes in processes, channel morphology and sedimentary environments. These changes form a context for the present paper.

Renwick and Ashley (1984) classified the fluvial–estuarine system into three zones for *fine sediment transfer*:

(i) transport zones – above the head of the tide;
(ii) temporary storage areas – upper and middle estuaries;
(iii) permanent sinks – mud benches, tidal marshes.

Renwick and Ashley (1984) also identified five zones of differing *channel type*, which can be related to the zones of fine sediment transfer.

(i) In the *transport zone*, the channel was described as narrow, shallow and bedrock-floored, where fine sediments were carried directly through in suspension.

Three channel types were identified across the second zone of *temporary storage* for fine sediment transfer:

(ii) a gravel-bed, braided zone near the head of the tide where some fine sediments are temporarily stored in the gravel;
(iii) a moderately deep, meandering, sandy-gravel channel in the upper estuary, where flows are fully reversing but seaward velocities are much higher than landward ones during floods so that sediments are flushed through;
(iv) a channel similar to (iii) but where higher salinities aid fine-grained sedimentation through flocculation and thus the development of adjoining salt marshes.

(v) The third zone of *permanent sinks* for fine sediment transfer was the lower estuary where extensive mud benches and salt marshes develop.

In addition to the sequence of downstream changes identified by Renwick and Ashley (1984), it is possible to conceptualize four zones of *tidal influence on flow*, moving in a downstream direction across the fluvial–tidal transition:

(i) the first zone is completely unaffected by tidal influences;
(ii) the second zone is subject to increased water depths and reduced flow velocities during the tidal cycle but does not experience flow reversal or salt-water penetration;

 

(iii) the third zone may be affected by flow reversal but only of fresh water;
(iv) the fourth zone is subject to flow reversal including the intrusion of some salt water.

These four zones of tidal influence on flow seem to correspond approximately to the five channel types identified by Renwick and Ashley, if channel types (iv) and (v) are associated with zone (iv) of tidal influence on flow.

The 18 km channel reach considered in this paper is located on the River Dee, on the English–Welsh border. It does not include tidal influence zone (iv). It is thus representative of the transition between a river-flow dominated regime (tidal influence zone (i) and channel type (i)), and a regime which is influenced by a fresh-water backwater without significant flow reversal (tidal influence zone (ii) and possibly the upstream component of tidal influence zone (iii); channel types (ii) and (iii)). The reach consists of a meandering channel with no braided section, identified as channel type (ii) by Renwick and Ashley (1984). However, analysis of the extent of sedimentation after a large flood, and bar exposure within the channel (Gurnell, 1996), shows that there is a zone of enhanced in-channel and floodplain sediment storage near the head of the tidally influenced channel (tidal influence zone (ii)) even though the channel exhibits a meandering rather than a braided form.

In addition to the downstream gradient in tidal influence, the study reach is also affected by a major backwater created by a tidal weir, and increasing reservoir regulation of river flows in recent years. Such a combination of influences is common on heavily managed European rivers and so represents an important area for research.

This paper summarizes existing research results on the hydrogeomorphology of the 18 km study reach, describes the preparation and analysis of channel cross-sectional surveys from 122 locations along the reach, and then assesses the process significance of the observed morphological trends. The possible relationship between channel form and process within the study reach is explored by identifying four stretches of river that are differently influenced by tides and the tidal weir. The extent to which recent flow regulation has affected channel form in each of these four stretches is also considered.

## HYDROGEOMORPHOLOGICAL CHARACTER OF THE STUDY REACH

The 18 km study reach of the River Dee (Figure 1) is located at the transition between the upstream, fluvially influenced river channel and downstream channel sections that are additionally affected by a fresh-water backwater during spring tidal cycles. The most downstream section of the reach contains a permanent backwater from Chester Weir (located some 20 km downstream). The study reach consists of a meandering planform (Figure 1c) with a highly sinuous course (sinuosity approximately 2·1). The reach contains at least 16 major meanders with a major meander wavelength slightly in excess of 500 m. The average channel width is approximately 30 m (limits of normal winter water level) and generalized bedslope ranges from 0·00005 $mm^{-1}$ in the most downstream section to 0·00065 $mm^{-1}$ at the upstream end of the reach.

The reach is of great geomorphological interest because it is one of the few examples of a downstream section of a major British river which has not been significantly channelized and straightened to improve navigation. Apart from some sporadic stone facing of the banks over the last few centuries, the author is not aware of any major channel works within this reach of the Dee. Thus, it represents a location where the geometry and size of the channel is relatively free to adjust to the transmitted discharge and sediment transport regime across the fluvial–tidal transition zone. In addition to this spatial trend in the character of the processes that may influence the geometry of the channel, there is also a temporal influence through progressive flow regulation during this century.

### *Influence of tidal cycles and the Chester Weir backwater*

Variations in water depth in the study reach are a function of river flow from the upstream catchment area, and tidal levels downstream (Weston, 1979). Unsteady flow conditions occur in the Lower Dee for up to 30% of the time as a result of tidal overtopping of Chester Weir (crest level approximately 4·4 m AOD). The effects range from minor pulses in river levels caused by slight overtopping of the weir to the effects of the highest spring tides which overtop the weir by a substantial margin causing flow reversal as far as Farndon (just

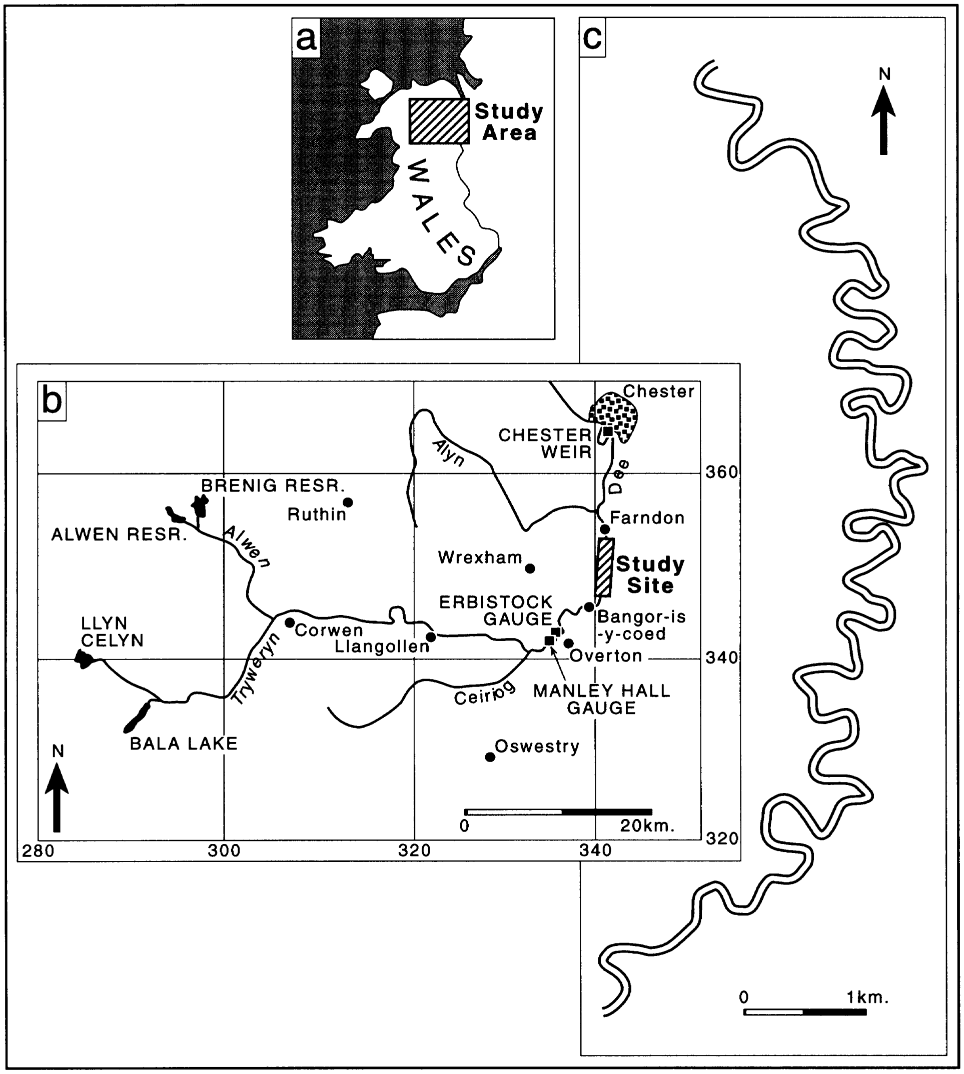


Figure 1. Location of the study reach.

downstream of the study reach) and backwater effects for a further 10 km upstream (Weston, 1979). The highest recorded tide at Chester Weir was 6·38 m AOD on 2 January 1976. The fresh-water flow from the River Dee just prior to the tide can have a considerable influence on the high tide level at Chester Weir and can influence river levels up to 30 km upstream and thus well into the study reach.

*Flow regulation*

Gurnell *et al*. (1994) report in detail on the nature of the tidal and flow regulation influences on this section of the Dee. In summary, the catchment area of the River Dee to Chester Weir (Figure 1) is 1817 $km^2$, and it generates a mean river flow of 37 $m^3 s^{-1}$ (Lambert, 1988). The reach has been affected by increasing river flow regulation since the early 19th century. Four major reservoirs affect the discharge of the river: the impounding Alwen Reservoir; Bala Lake, whose storage is now regulated; and the regulating reservoirs Llyn Celyn and Llyn Brenig. The river flow regime has changed noticeably since the mid-1960s as a result of the closure of Llyn Celyn (in 1965) followed by Llyn Brenig (in 1979). The most noticeable changes in the river discharge regime have been a steady decline in the level of the annual instantaneous maximum flows over the period 1938–1992

 

and a decrease in the annual range of monthly maximum instantaneous flows since the mid-1960s. For example, the mean annual flood is 14 per cent smaller for the period 1965–1992 in comparison with 1946–1963. The range in mean monthly flows also shows decreasing variability, with a marked increase in the annual minimum of the mean monthly flows since the mid-1960s. The considerable literature on the morphological impact of flow regulation (e.g. Petts, 1984; Carling, 1988) suggests that these changes might be expected to have a noticeable impact on the morphology of the study reach by 1973, the date of the morphological survey which is analysed in this paper.

### *Trends in river planform*

Gurnell *et al*. (1994) and Gurnell (1997) undertook Geographical Information System (GIS)-based analyses of planform change on the study reach using digitized boundaries from five sets of historical maps (1876, 1897, 1909, 1949 and 1979) and six sets of air photographs (1946, 1951, 1966, 1974, 1985 and 1992) at approximately 1:10 000 scale, representing the period of the last 115 years. The conclusions from these analyses that are relevant to the present discussion are as follows.

1. The channel planform is surprisingly stable.
2. There is a *spatial trend* of increasing positional stability and decreasing channel width down the study reach. This can be associated with decreasing stream power down the reach as a result of decreasing bed slope and the increasing influence of the backwater from Chester Weir and from high tidal levels overtopping the weir crest. Whereas there has been consistent channel migration since the late 19th century at a few sites, which are located in the upstream and central portions of the reach, the predominant modes of channel planform change in the lower sections of the reach are either no identifiable movement or an alternating, oscillatory pattern in channel position.
3. There is also a *temporal trend* within the historical data, where the most notable changes have occurred during the period of marked increase in the regulation of the river flows. Since the 1950s the channel has narrowed and the narrowing appears to have propagated downstream to the central portion of the reach by the 1970s and the downstream portion by 1992.

## DATA PREPARATION

In 1973, the Dee and Clwyd River Authority undertook a detailed topographic survey of the River Dee valley from Farndon to Bangor. This included the survey of 156 river channel cross-sections spaced at 150 m intervals along the river centre line. Of these cross-sections, 122 fall within the study reach (Figure 1) and provide the information upon which the following analyses are based.

The cross-section profiles were digitized to the nearest 0·1 m to support analyses of the geometry of the sections. Various properties of the geometry of the cross-sections were estimated at 0·2 m vertical increments through each channel cross-section from the level of the surrounding floodplain to approximately the vegetation limit on the banks (*csa*, cross-sectional area in $m^2$; *P*, wetted perimeter in m; *w*, width at the upper limit of the cross-section in m; *dmax*, maximum depth in m; *dbar*, mean depth (i.e. *csa*/*w*) in m; *R*, hydraulic radius (i.e. *csa*/*P*) in m; and *w*:*dbar*, width:mean depth ratio, which is dimensionless). Plots of altitude (m AOD; i.e. above the Ordnance Survey Datum) against *w*:*dbar* for each cross-section were used to identify minima in the width:mean depth ratio. The minimum width:depth ratio has been used (e.g. Wolman, 1955; Pickup and Warner, 1976) to identify the 'bankfull' level which corresponds to the bankfull discharge, a discharge which is assumed to have channel-forming significance. Other minima in the width:mean depth ratio may also be indicative of water or flow levels which may have particular significance for channel form. Up to three minima were identified in each of the cross-sections and the values of the geometric properties at each of these levels were subjected to further analysis. These three levels were numbered 1 to 3 from the highest level downwards. Level 1 was identified at all 122 cross-sections, level 2 at 57 cross-sections, and level 3 at 36 cross-sections (Table I).

In the light of known influences on water levels and flow velocities along the study reach, four stretches were defined (Figure 2). The long-profile of the study reach was established using the topographically lowest points

 

Table I. Terms used to describe field locations in the text

| | | |
|---|---|---|
| Reach | The entire 18 km of channel analysed. | |
| Stretch | Four horizontal subdivisions of the study reach: | |
| | Stretch 1 | *The most downstream subdivision* of the study reach. Water levels are influenced by river flows, the backwater from Chester Weir and high tidal levels. |
| | Stretch 2 | Immediately upstream from stretch 1 and separated from it by a local high point on the long profile of the channel. Water levels in this section are influenced by river flows, the backwater from Chester Weir and high tidal levels. |
| | Stretch 3 | Immediately upstream from stretch 2. Water levels are unaffected by the backwater from Chester Weir, but are influenced by very high tidal levels and by river flows. |
| | Stretch 4 | *The most upstream subdivision* of the study reach. Water levels are influenced by river flows alone. |
| Level | Up to three vertical levels within the channel cross-section have been identified from local minima in the width:mean depth ratio. | |
| | Level 1 | *The highest level* identified, usually very close to the level at which water would start to spill out of the channel onto the floodplain. This level is identified for all 122 surveyed cross-sections along the study reach of which 42 are in stretch 1, 30 in stretch 2, 28 in stretch 3, and 22 in stretch 4. |
| | Level 2 | *An intermediate level* identified in 57 of the 122 cross-sections (21 in stretch 1, 11 in stretch 2, 12 in stretch 3 and 13 in stretch 4) |
| | Level 3 | *The lowest level*, identified in 36 of the 122 surveyed cross-sections (16 in stretch 1, 17 in stretch 2, 3 in stretch 3, 0 in stretch 4) |

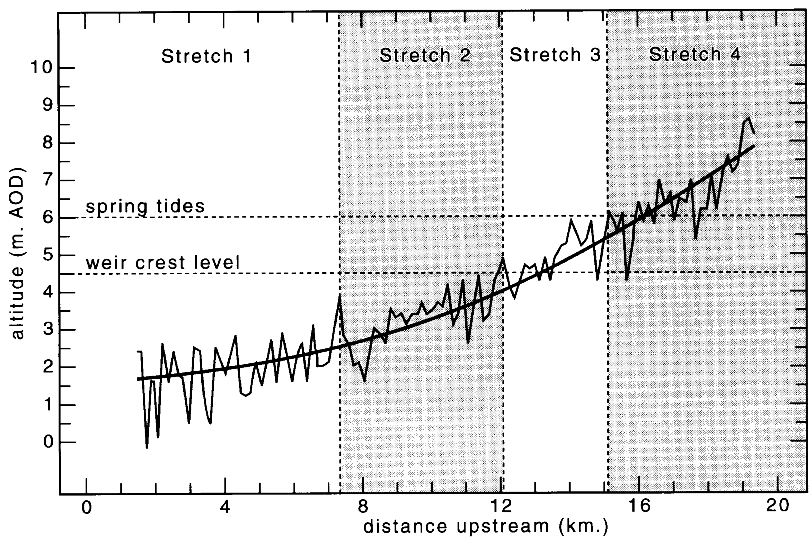


Figure 2. Long-profile of the study reach showing the boundaries of four stretches within the reach.

on each of the 122 cross-sections. The reach was split into two main stretches at the level of the crest of Chester Weir (4·4 m AOD). These two stretches were also subdivided. The downstream stretch was split at a local high point in the river bed, which almost reached the level of the crest of Chester Weir (Figure 2). It was thought likely that such a high point could have a strong influence on water and sediment movements and thus may have influenced channel geometry. The upstream stretch was split at a bed elevation of 6 m AOD, representing the upper limit of commonly occurring spring tide levels. This limit is somewhat arbitrary, but because of the increasing bedslope in this part of the study reach, an error of the order of +/–0·2 m would make little difference to the spatial location of the stretch boundaries and would also correspond to the precision used in identifying width:depth minima in the surveyed cross-sections. The stretches were numbered 1 to 4 in an upstream direction (Figure 2).

Thus, information was available concerning the geometry of river cross-sections to morphologically identified levels within four stretches of the study reach. A comparison of cross-section levels and stretches

 

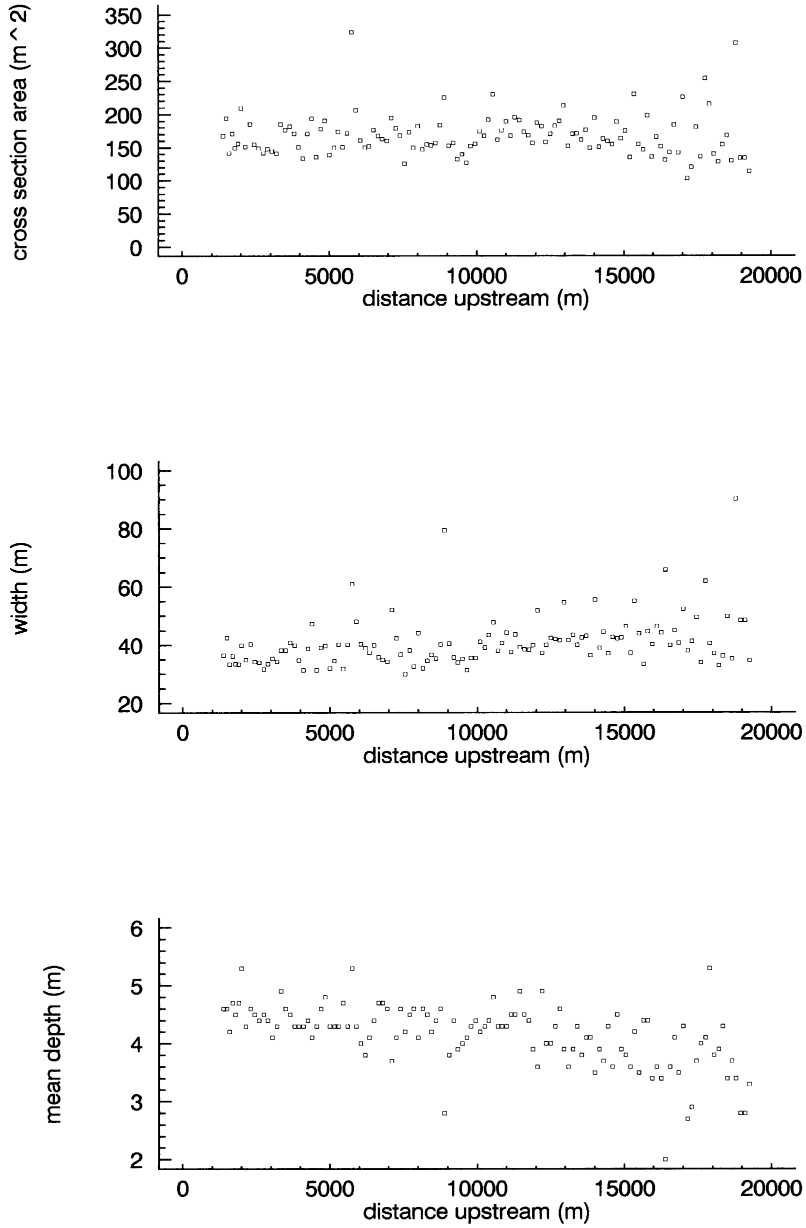


Figure 3. The cross-sectional area ($m^2$), width (m) and mean depth (m) of the channel cross-section to level 1 along the study reach.

shows that level 3 does not occur in any of the cross-sections in stretch 4 and only has three occurrences in stretch 3, but levels 1 and 2 are identifiable in cross-sections along the entire study reach.

The terms *reach*, *stretch* and *level* will be used throughout the following discussion and so their meaning is defined for reference in Table I.

## DOWNSTREAM TRENDS IN CHANNEL GEOMETRY

Figures 3 to 5 plot the trend in *csa*, *w* and *dbar* for each of the three cross-section levels. It is interesting to note that whereas the level 2 and 3 cross-section areas decrease in an upstream direction, the cross-section area to

 

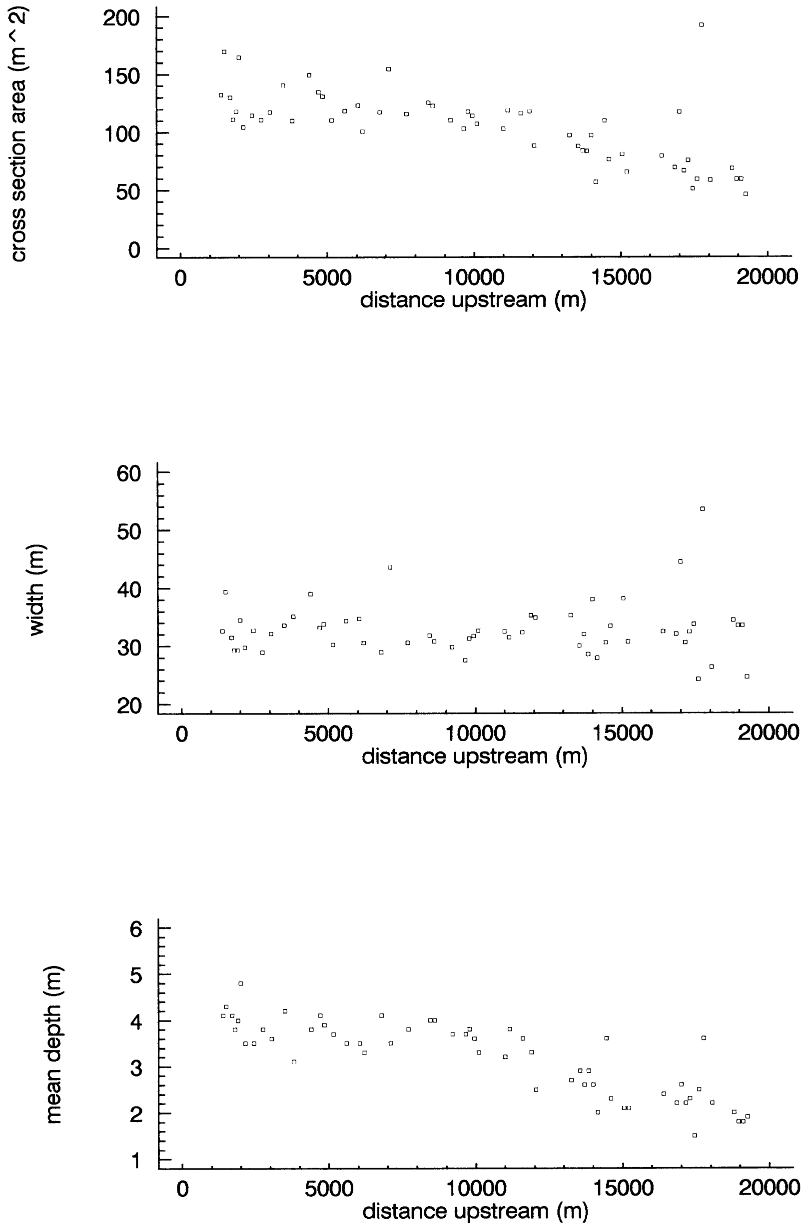


Figure 4. The cross-sectional area ($m^2$), width (m) and mean depth (m) of the channel cross-section to level 2 along the study reach.

level 1 shows no linear upstream trend. In the former cases the upstream decrease in cross-section area is achieved by a decrease in mean depth, whereas in the latter case, the cross-section area is maintained by an upstream increase in channel width, which counteracts a decrease in channel depth.

In order to identify the form of the spatial trend in each of the geometric properties at each of the three levels, a variety of regression models was estimated. In each case a regression model was estimated for the entire study reach so that trends along the reach could be described, and so that the statistical significance of apparent differences in the trends between stretches within the reach could be established through the use of dummy variables. Three types of regression model were estimated.

 

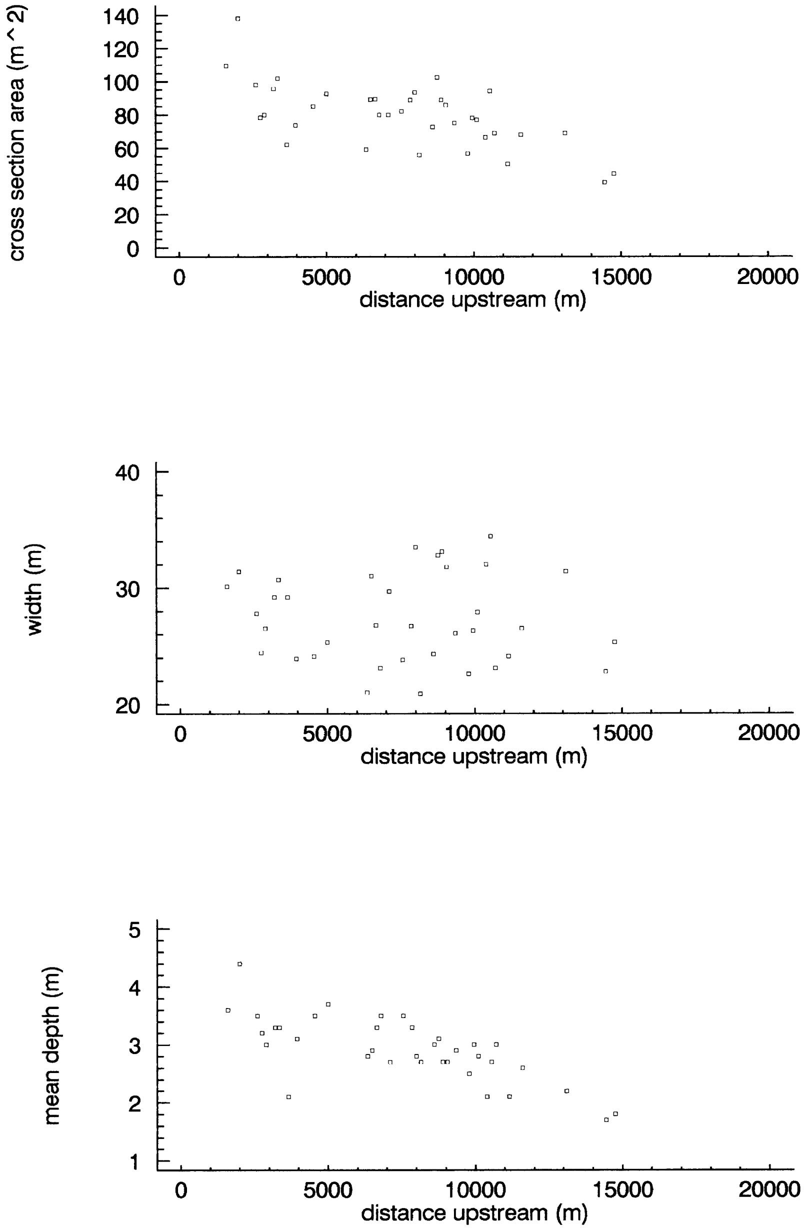


Figure 5. The cross-sectional area ($m^2$), width (m) and mean depth (m) of the channel cross-section to level 3 along the study reach.

1. Simple linear regression analysis estimated whether there was any significant linear trend in each geometric property with distance along the study reach.
2. Quadratic regression models, using upstream distance and distance squared as the independent variables, estimated whether there was any significant simple non-linear trend in each geometric property with distance along the study reach.
3. Linear regression models using upstream distance as the independent variable coupled with a variety of dummy variables to represent individual stretches and groups of stretches, identified whether there was any significant difference in the form of the linear trend in each geometric property within each of the four stretches of the reach.

 

Table II. Upstream trends in selected geometric properties estimated using linear regression analysis

| | | | Adj. $R^2$ |
|---|---|---|---|
| *csa* | level 1 | no significant regression relationship | |
| | level 2 | $csa = 141{\cdot}8 - 4{\cdot}0 \times 10^{-3}\, y$ | 0·450 |
| | | **$csa = 129{\cdot}2 - 1{\cdot}8 \times 10^{-7}\, y^2$** | 0·463 |
| | level 3 | $csa = 106{\cdot}0 - 3{\cdot}0 \times 10^{-3}\, y$ | 0·384 |
| | | **$csa = 95{\cdot}0 - 2{\cdot}2 \times 10^{-7}\, y^2$** | 0·386 |
| *w* | level 1 | **$w = 34{\cdot}9 + 6 \times 10^{-4}\, y$** | 0·121 |
| | level 2 | no significant regression relationship | |
| | level 3 | no significant regression relationship | |
| *dbar* | level 1 | $dbar = 4{\cdot}7 - 6{\cdot}0 \times 10^{-5}\, y$ | 0·316 |
| | | **$dbar = 4{\cdot}5 - 2{\cdot}8 \times 10^{-9}\, y^2$** | 0·337 |
| | | $dbar = 4{\cdot}6 - (4{\cdot}0 \times 10^{-5} + 1{\cdot}7 \times 10^{-6}\, dum4)\, y$ | 0·335 |
| | level 2 | $dbar = 4{\cdot}4 - 1{\cdot}0 \times 10^{-4}\, y$ | 0·696 |
| | | $dbar = 4{\cdot}0 - 5{\cdot}7 \times 10^{-9}\, y^2$ | 0·729 |
| | | **$dbar = 4{\cdot}0 - (4{\cdot}0 \times 10^{-5} + 6{\cdot}0 \times 10^{-5}\, dum3\&4)\, y$** | 0·764 |
| | level 3 | $dbar = 3{\cdot}8 - 1{\cdot}2 \times 10^{-4}\, y$ | 0·516 |
| | | **$dbar = 3{\cdot}4 - 7{\cdot}6 \times 10^{-9}\, y^2$** | 0·567 |
| *w*:*dbar* | level 1 | $w{:}dbar = 6{\cdot}9 + 3{\cdot}3 \times 10^{-4}\, y$ | 0·202 |
| | | **$w{:}dbar = 8{\cdot}1 + 1{\cdot}6 \times 10^{-8}\, y^2$** | 0·214 |
| | level 2 | $w{:}dbar = 6{\cdot}4 + 4{\cdot}6 \times 10^{-4}\, y$ | 0·557 |
| | | $w{:}dbar = 7{\cdot}8 + 2{\cdot}3 \times 10^{-8}\, y^2$ | 0·619 |
| | | **$w{:}dbar = 8{\cdot}8 + 2{\cdot}3\, dum4 + 2{\cdot}5 \times 10^{-4}\, dum3\&4\, y$** | 0·664 |
| | level 3 | $w{:}dbar = 6{\cdot}7 + 4{\cdot}1 \times 10^{-4}\, y$ | 0·317 |
| | | **$w{:}dbar = 7{\cdot}8 + 2{\cdot}8 \times 10^{-8}\, y^2$** | 0·373 |
| *R* | level 1 | $R = 4{\cdot}2 - 4{\cdot}4 \times 10^{-5}\, y$ | 0·289 |
| | | $R = 4{\cdot}0 - 2{\cdot}2 \times 10^{-9}\, y^2$ | 0·330 |
| | | **$R = 3{\cdot}9 + (1{\cdot}2 - 1{\cdot}0 \times 10^{-4}\, y)\, dum3\&4$** | 0·348 |
| | level 2 | $R = 3{\cdot}9 - 9{\cdot}8 \times 10^{-5}\, y$ | 0·683 |
| | | $R = 3{\cdot}6 - 4{\cdot}8 \times 10^{-9}\, y^2$ | 0·722 |
| | | **$R = 3{\cdot}6 - (3{\cdot}6 \times 10^{-5} + 5{\cdot}0 \times 10^{-5}\, y)\, dum3\&4)\, y$** | 0·752 |
| | level 3 | $R = 3{\cdot}4 - 9{\cdot}7 \times 10^{-5}\, y$ | 0·518 |
| | | $R = 3{\cdot}1 - 6{\cdot}3 \times 10^{-9}\, y^2$ | 0·570 |
| | | **$R = 2{\cdot}9 + (1{\cdot}2 - 1{\cdot}6 \times 10^{-4}\, y)\, dum2$** | 0·603 |

*csa*, cross-sectional area ($m^2$); *w*, channel width (m); *dbar*, mean channel depth (m); *w*:*dbar*, channel width:mean depth ratio (dimensionless); *R*, hydraulic radius (m); *y* distance (m) measured in an upstream direction from the downstream end of the reach. Dummy variables: *dum4*=1 for stretch 4, otherwise 0; *dum2*=1 for stretch 2, otherwise 0; *dum3&4*=1 for stretches 3 and 4, otherwise 0. **Equations in bold have the highest adjusted $R^2$ for each level.** Only equations whose slope coefficients are significantly different from zero ($P<0{\cdot}05$) are tabulated.

Table II lists the regression models that yield the highest coefficient of determination (adjusted for the degrees of freedom) for each of the three model types defined above, but includes only those models where the slope terms are all significantly different from zero ($P<0{\cdot}05$). Several general observations can be drawn from Table II.

- The very small slope coefficients are a function of the units used (distance upstream is represented in m).
- The ‘best’ model in representing the form of the upstream pattern for each level – geometric property combination is selected on the basis of the highest adjusted $R^2$ value. In most cases this ‘best’ model represents a marked increase in the coefficient of determination in comparison with the ‘second best’ model. This indicates that the form of the ‘best’ model provides a genuinely enhanced description of the changes in the geometric property with distance along the study reach.
- The coefficient of determination for many of the estimated regression models is quite small, illustrating that much of the variance results from other (probably local) factors rather than trend along the study reach. However, coefficients of determination are generally quite high for the models estimated for level 2 (second highest values are associated with level 3). Furthermore, the ‘best’ models for level 2 incorporate dummy variables, suggesting that there are distinct differences in the estimated relationships between

 

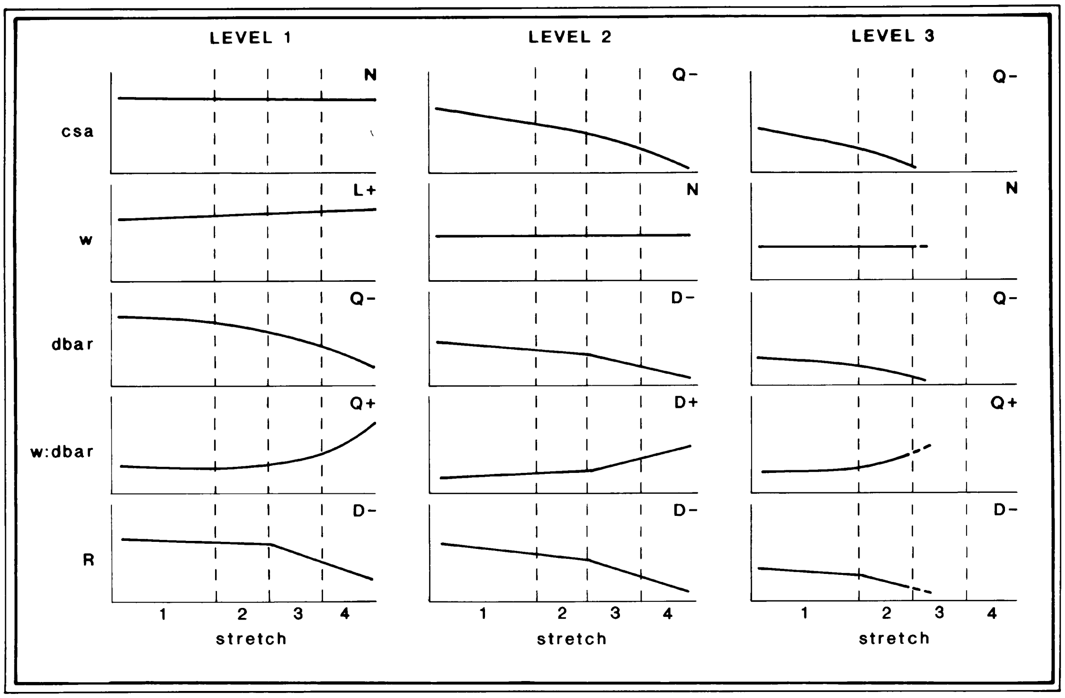


Figure 6. Schematic form of the upstream trend in *csa*, *w*, *dbar*, *w*:*dbar* and *R* at three horizontal levels in the channel cross-section defined by minima in the width:mean depth ratio (left column, level 1; central column, level 2; right column, level 3) within the study reach. The form of the upstream trend is denoted by N (no trend), L (linear trend), Q (curved, quadratic trend), and D (linear trend with thresholds identified through the use of dummy variables); and, for L, Q and D, by + (upstream increase) or – (upstream decrease).

stretches, particularly between the two downstream (1 and 2) and the two upstream (3 and 4) stretches which are differentiated by the influence of the Chester Weir backwater.

Figure 6 summarizes schematically the form of the upstream trend in *csa*, *w*, *dbar*, *w*:*dbar* and *R* at each of the three levels as represented by the 'best' regression models. It further illustrates that a threshold in the upstream trend appears to occur at the boundary between stretches 2 and 3 in several of the plots, particularly those representing trends for level 2. A threshold also appears between stretches 1 and 2 in the hydraulic radius of level 3 cross-sections. Even where statistically significant changes of slope do not provide the best representation of upstream trends, the quadratic curves estimated for many of the geometric properties result in rapidly increasing slopes in the upstream sections of the trend lines. These changes in slope are particularly marked within stretches 3 and 4.

Having identified the form of the trends in individual geometric properties along the entire channel reach, discriminant function analysis was used to explore the degree to which the aggregate geometry of channels within the four stretches could be identified as being distinct in character. Discriminant function analysis was applied to the geometric variables for each of the three channel levels. In one set of analyses, all of the geometric properties (*dbar*, *dmax*, *w*, *w*:*dbar*, *R*, *csa* and *P*) were included. For levels 1 and 2, using Bartlett's $\chi^2$ test, only the first discriminant function was significant, whereas at level 3, the second discriminant function was also significant. Table III lists the standardized coefficients for each of the variables for the first discriminant function estimated in the analyses of data for each of the three channel levels and illustrates that all of the geometric properties, apart from dmax, contribute strongly towards discrimination for at least one of the channel levels. Nevertheless, geometric properties of river channels are highly correlated, and so a second discriminant function analysis was based on only three variables (*csa*, *w* and *R*) to represent three contrasting dimensions of the channel: size, width and shape. Table IV summarizes the classification results for each of

Table III. Standardized coefficients for the first discriminant function for each channel level

| Variable | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| *dbar* | –0·76 | 2·58 | –0·67 |
| *dmax* | 0·48 | –0·56 | 0·03 |
| *w* | 2·13 | 3·35 | 1·60 |
| *w*:*dbar* | –1·09 | –0·51 | –3·04 |
| *R* | 3·27 | –5·40 | 1·26 |
| *csa* | –4·32 | 3·32 | –3·24 |
| *P* | 2·03 | –4·30 | 2·56 |

Table IV. Classification results (expressed as percentages of the cross-sections in the four channel stretches) based upon discriminant function analysis of geometric properties of the channel cross-section

| | Actual group (stretch) | Sample size | Predicted group (stretch) | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| Analysis based on seven variables (*dbar*, *dmax*, *w*, *w*:*dbar*, *R*, *csa*, *P*) | | | | | | |
| level 1 | 1 | 42 | 50 | 31 | 17 | 2 |
| | 2 | 30 | 47 | 37 | 13 | 3 |
| | 3 | 28 | 7 | 18 | 61 | 14 |
| | 4 | 22 | 5 | 5 | 27 | 64 |
| level 2 | 1 | 21 | 57 | 43 | 0 | 0 |
| | 2 | 11 | 27 | 73 | 0 | 0 |
| | 3 | 12 | 0 | 9 | 67 | 25 |
| | 4 | 13 | 0 | 0 | 15 | 85 |
| level 3 | 1 | 16 | 69 | 25 | 6 | |
| | 2 | 17 | 18 | 76 | 6 | |
| | 3* | 3 | 0* | 33* | 67* | |
| Analysis based on three variables (*w*, *R*, *csa*) | | | | | | |
| level 1 | 1 | 42 | 57 | 26 | 12 | 5 |
| | 2 | 30 | 40 | 40 | 17 | 3 |
| | 3 | 28 | 18 | 18 | 36 | 29 |
| | 4 | 22 | 0 | 9 | 18 | 73 |
| level 2 | 1 | 21 | 43 | 52 | 0 | 5 |
| | 2 | 11 | 18 | 73 | 9 | 0 |
| | 3 | 12 | 17 | 0 | 58 | 25 |
| | 4 | 13 | 0 | 0 | 23 | 77 |
| level 3 | 1 | 16 | 75 | 19 | 6 | |
| | 2 | 17 | 18 | 76 | 6 | |
| | 3* | 3 | 0* | 33* | 67* | |

* Sample of only three cross-sections

these analyses. It appears that whether all variables or only *csa*, *w* and *R* are included in the analysis, similar conclusions can be drawn.

- At level 1, the geometric characters of stretches 1 and 2 are indistinguishable, but stretches 3 and 4 overlap little with each other or with 1 and 2. Thus at level 1, the combined impact of upstream increasing channel width and decreasing hydraulic radius within stretches 3 and 4 distinguishes these stretches from one another and also from stretches 1 and 2.
- At level 2, stretches 1 and 2 are not well distinguished but the remaining stretches appear to be distinguishable from one another. Thus upstream decreasing cross-section area, decreasing mean depth,

 

and decreasing hydraulic radius distinguishes stretches 3 and 4 from one another and from stretches 1 and 2.

- At level 3, stretch 3 only contains three cross-sections and so little confidence can be placed in the results for this stretch, but stretches 1 and 2 can be readily distinguished. Thus, at level 3, decreasing cross-section area and hydraulic radius distinguish stretch 1 from stretch 2.

The statistical significance of these apparent differences between the stretches was tested by applying one-way analysis of variance to the scores for each cross-section on discriminant function 1 within each of the four stretches of the study reach. ANOVA suggested the same discrimination between stretches, regardless of the number of variables used to estimate the discriminant function. The analysis indicated no significant difference in the scores for stretches 1 and 2 at levels 1 and 2, but all other stretches were significantly different from one another at these two levels ($P<0{\cdot}05$). At level 3, the scores on the first discriminant function were significantly different ($P<0{\cdot}05$) between stretches 1 and 2.

## THE PROCESS SIGNIFICANCE OF THE DOWNSTREAM TRENDS IN CHANNEL GEOMETRY

Figure 7 schematically plots average mean depth and the average width of the three morphologically defined levels for the four stretches of the study reach in comparison with the mean of the maximum depth and the levels of the Chester Weir crest. The downstream channel narrowing previously identified from historical planform sources is indicated in Figure 7 only at level 1, where an approximately constant channel capacity is maintained by a complementary increase in downstream mean channel depth. Levels 2 and 3 do not indicate any significant downstream trend in channel width, but increasing mean depth results in an increase in channel capacity at these two levels downstream. Figure 7 also shows how levels 2 and 3 rise and become laterally less distinct in the downstream direction within the form of the outer channel defined by level 1.

Within stretch 4, the channel form is dependent upon fluvial processes, although it is conceivable that the cumulative impact of high tides combined with high river levels may extend occasionally into the lower part of this stretch. Nevertheless, a first stage in understanding the geomorphological processes within the study reach as a whole is to assess the degree to which the channel within stretch 4 appears to be adjusted to the current river flow regime. One way of doing this is to estimate the degree to which different discharges and sediment transport regimes may be associated with levels 1 and 2 using Manning's equation in combination with a sediment transport equation.

The Manning equation for open channel flow was applied to all channel cross-sections in the fluvially dominated stretch 4, and to the geometry of cross-sections conforming to levels 1 and 2 using the local bedslope and a Manning's *n* of 0·04. This relatively high value of Manning's *n* was estimated from steady-state analysis of the reach to replicate flow rating curves along the river prior to hydraulic modelling (Welsh Water Authority, 1980), and reflects the flow resistance presented by the high sinuosity of the river channel. The discharge estimates fall in the range 114–341 $m^3 s^{-1}$ for level 1 and 40–82 $m^3 s^{-1}$ for level 2. Therefore, it appears that the current channel of the River Dee to level 1 is of approximately the capacity required to accommodate floods of a 1·5–2·3 year return period (estimated from the annual maximum series, 1965–92). 'A return period of between one and three years with a modal value of about 1·5 years, using the annual series, has been established for a range of rivers' (Petts and Foster, 1985) to be the expected discharge at which flows start to spill out of the channel and this is certainly the case for the River Dee.

To identify the process significance of level 2, further analysis of flow and sediment transport data was undertaken, involving the combination of flow frequency estimates with a sediment rating curve to estimate the discharge which is dominant in transporting sediment (e.g. Hey, 1979). Unfortunately no bedload transport information is available for the study reach of the River Dee and the suspended sediment transport data are very limited, so the Bagnold (1966, 1980) stream power function was used to estimate bedload transport rates for three of the cross-sections in stretch 4 so that the dominant discharge for sediment transport of different median grain size could be estimated. The estimates produced using a bedload transport equation cannot be expected to be correct in absolute terms, although their relative values from reach to reach are likely to be indicative of true

 

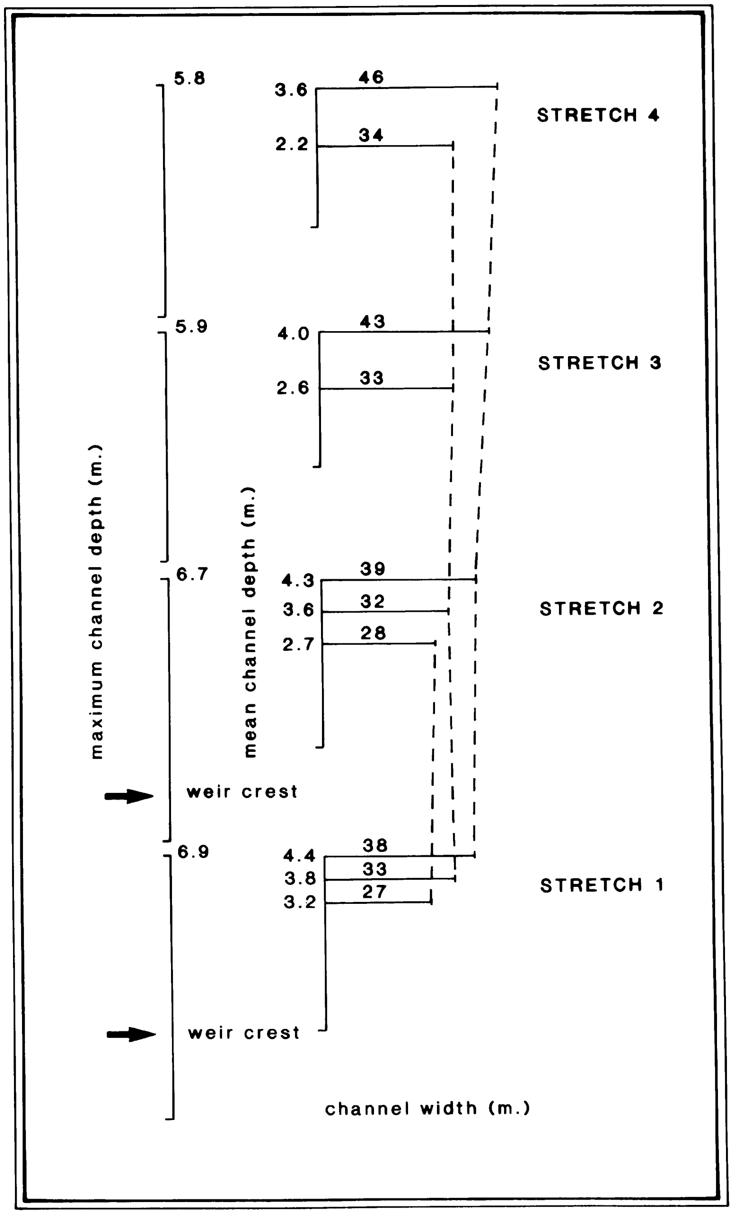


Figure 7. Average mean depth and average width for the three morphologically defined levels in comparison with mean maximum depth and the level of the Chester Weir crest within the four stretches of the study reach.

differences in bedload transport rates. Apart from the problems of the absolute accuracy of the estimates, the Bagnold function makes no allowance for the impact of restricted sediment supply, including the effects of armouring of the channel bed. Furthermore, the discharge estimates used in the computations are generalized to the extent that they are based on an energy slope derived from a smoothed bed profile and they do not take account of channel curvature. The Bagnold function provides estimates of transport rates given a median particle size for the bed material. Four different median grain sizes (0·1, 0·5, 1 and 4 mm) were used in the present analysis, although it is accepted that the true ranges of particle size represented by the analyses are probably very different from those specified.

 

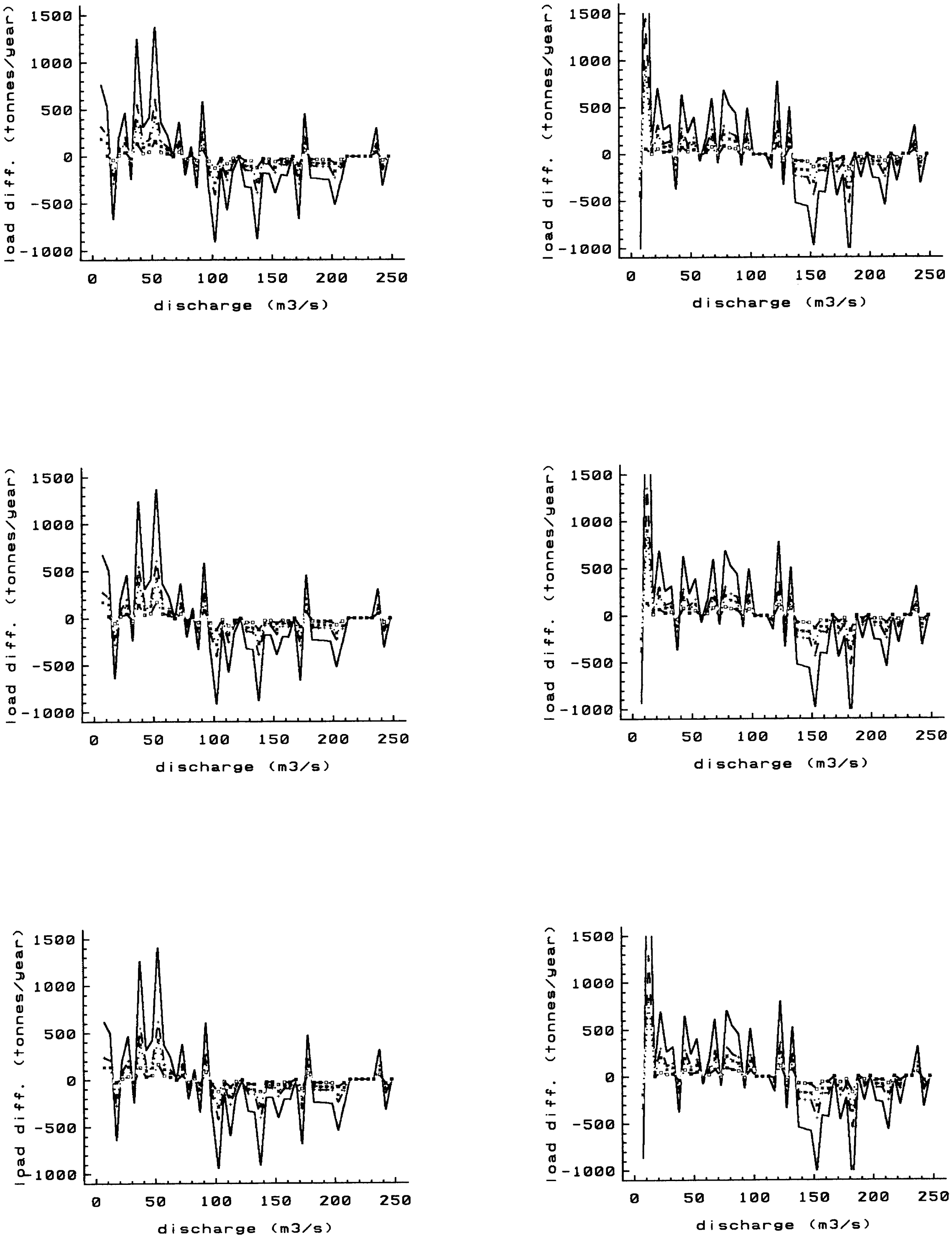


Figure 8. The difference in estimated sediment transport rate between regulated and naturalized flow regimes for a range of particle sizes within three cross-sections in stretch 4, for 1970–73 (left) and 1986–89 (right). The curves represent particle sizes of 4 (—□—), 1 (...*...), 0·5 (--+--) and 0·1mm (——).

Table V. Estimates of the discharges associated with enhanced sediment transport of three particle sizes under regulated in comparison with naturalized flows (discharge estimates are based on a class interval of 5 $m^3 s^{-1}$) for one cross-section within river channel stretch 4

| Time period and sediment size (mm) | Discharge estimates ($m^3 s^{-1}$) | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1970–73 | | | | |
| 0·5 | 20 | 75 | 47·5 | 7·5 |
| 1·0 | 20 | 75 | 47·5 | 7·5 |
| 4·0 | 20 | 75 | 47·5 | – |
| 1974–77 | | | | |
| 0·5 | 35 | 95 | 65 | 7·5 |
| 1·0 | 35 | 95 | 65 | 7·5 |
| 4·0 | 35 | 95 | 65 | – |
| 1978–81 | | | | |
| 0·5 | 30 | 90 | 60 | 12·5 |
| 1·0 | 30 | 90 | 60 | 12·5 |
| 4·0 | 30 | 90 | 60 | – |
| 1982–85 | | | | |
| 0·5 | 45 | 95 | 70 | 12·5 |
| 1·0 | 45 | 95 | 70 | 12·5 |
| 4·0 | 45 | 95 | 70 | – |
| 1986–89 | | | | |
| 0·5 | 10 | 100 | 55 | – |
| 1·0 | 10 | 100 | 55 | – |
| 4·0 | 20 | 100 | 60 | – |

1, Lower limit of discharge showing an increase in sediment transport of all listed grain sizes under regulated in comparison with naturalized flows; 2, upper limit of discharge showing an increase in sediment transport of all listed grain sizes under regulated in comparison with naturalized flows; 3, mid-point of the discharge range shown under 1 and 2; 4, mid-point of the range of discharges exhibiting an increase in finer (0·5 and 1·0 mm) sediment transport under regulated in comparison with naturalized flows.

Sediment rating curves for each particle size were estimated for three of the cross-sections in stretch 4 by combining estimates of discharge and estimates of sediment transport rate for a range of water levels. These sediment rating curves can be combined with the frequency of particular ranges of discharge to identify the discharge range which is likely to be responsible for transporting the greatest load of sediment (the dominant discharge) for each of the four particle sizes within each of the three cross-sections. The load of each particle size transported as an annual average by the regulated and naturalized flow regimes for the periods 1970–73 and 1986–89 were then estimated. Figure 8 plots the difference between the regulated and naturalized bedload transport frequency patterns during 1970–73 (left) and 1986–89 (right) for the three selected cross-sections. Flow regulation has resulted in virtually all sediment being tranported by flows in the range 5–100 $m^3 s^{-1}$, whereas higher flows were able to make a significant contribution to sediment transport under the naturalised flow regime. In Table V, components of the pattern of sediment transport for five different time periods are presented for one channel cross-section as an illustration of the estimated impact of flow regulation on the sediment transport regime for the whole of stretch 4. Table V implies that as a result of the changed flow regime, there is an increase in finer sediment transport at very low flows, which is a function of the substantial increase in flow frequency at around 10–15 $m^3 s^{-1}$ under flow regulation. The mid-point of the 5 $m^3 s^{-1}$ discharge class in which this enhanced finer sediment transport occurs is summarized in column 4 of Table V. In addition, there is a range in discharge over which enhanced sediment transport occurs for all grain sizes presented. The lower limit (column 1), upper limit (column 2) and mid-point (column 3) of this enhanced sediment transport under regulated flow is also listed in Table V. The mid-point falls in the range 47·5–70·0 $m^3 s^{-1}$ for all of the years analysed, which corresponds closely with the interquartile range of discharge estimates for flow stages to level

 

2 in stretch 4. This suggests that level 2 may be associated with the 5–100 $m^3 s^{-1}$ discharge range that transports most of the sediment under the present regulated flow regime, and that it may at least partly reflect the impact of the increase in sediment transport that is associated with discharges in the range 50–70 $m^3 s^{-1}$. Surveys of the sedimentary structure of the bank deposits confirm this explanation.

Because level 2 is identifiable through river stretches 1, 2 and 3, it can tentatively be suggested that this level reflects the interaction of the current river flow and sediment transportation regime with the tidal backwater which affects all of these three stretches. Level 3, which only occurs within stretches 1 and 2, can be inferred to be associated with the static backwater controlled by Chester Weir. Since level 3 exceeds the level of the weir crest by approximately 2 m, it is likely that it reflects the impact of the river discharge and sediment transport regime during the 70 per cent of the time when tidal overtopping of Chester Weir is not occurring.

## SUMMARY AND CONCLUSIONS

This paper has presented a morphological analysis of 122 channel cross-sections extending across a transition from fluvial to fluvial–tidal to fluvial–tidal–weir influences, from which a number of conclusions can be drawn.

1. The morphology of the cross-section of the river channel along an 18 km reach that extends across the zone of tidal and weir influences, changes in a clearly identifiable manner. Up to three minima in the width:mean depth ratio identify channel levels with distinguishable morphologies whose geometric properties exhibit clear downstream trends. In particular, level 1 defines a channel which becomes narrower and deeper in a downstream direction, thereby maintaining an approximately constant cross-sectional area. Levels 2 and 3 describe channel cross-sections which increase in cross-sectional area in a downstream direction by maintaining an approximately constant width but by increasing in depth. Whilst level 3 is only consistently identified in stretches 1 and 2 (which are influenced by the Chester Weir backwater), trends in the geometric properties of level 2 cross-sections along the study reach appear to change in slope at the limit of the weir backwater.
2. If the study reach is subdivided into four stretches at the upstream boundaries of the tidal and weir influences, and at a high point in the channel bed within the backwater zone of the weir, it is possible to establish statistically significant differences in the geometry of the river channel cross-sections between the four stretches.
3. Estimation of the flows and sediment transport associated with levels 1 and 2 within stretch 4, using simple modelling approaches, suggests that level 1 is adjusted to flows within the 1·5 to 2·33 year return period under the present flow regime, and that level 2 may be associated with the dominant discharge for sediment transport and its adjustment as a result of flow regulation. These suggestions require confirmation through a combination of field investigations of the structure of the bank sediments within stretches influenced to different degrees by hydraulic disturbances.

At present the inferences concerning the processes controlling the geometry of this 18 km reach of the River Dee must be considered speculative. However, this analysis has established a pronounced change in channel geometry that can be correlated with zones of differing hydraulic disturbance within the study reach. Of particular interest is the maintenance of channel capacity by a decrease in width and increase in depth of the bankfull channel (level 1) in a downstream direction. This is a trend which, to the author’s knowledge, has not been reported elsewhere, and which appears from field observations to result from a transition in the dominant processes controlling the bank profile. Gurnell *et al.* (1994) and Gurnell (1997) reported a decrease in lateral channel mobility in a downstream direction on the study reach with a decrease in any consistent lateral movements in channel position and an increase in alternating, oscillatory behaviour in bank movements. In the field, there are clear signs of bank instability throughout the reach. Therefore, this instability that can be seen in the field must be ‘self-healing’, particularly in stretches 1 and 2. The downstream increase in the average bank slope observed by the above analyses (e.g. Figure 7) and the increasing wetting and drying cycles induced by the downstream tidal influence, presumably render the banks more susceptible to failure in stretches 1 and 2 than upstream. Thus, bank movement here is probably controlled more by bank hydrological processes than by fluvial processes, particularly in stretches 1 and 2, but to some extent also in stretch 3. Bank failure scars may induce identifiable levels in the bank profile. It also appears from field observation that a process of sediment

 

draping across the surfaces of the banks rebuilds them in the downstream stretches of the reach, resulting in a cyclic pattern of failure and stabilization, and relatively steep bank profiles. The level to which sediment draping occurs depends upon the interaction of river flows, tides and the Chester Weir backwater, also leading to identifiable levels in the channel cross-section.

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